Regional Small-Event Identification Using Seismic Networks and Arrays

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Abstract

In view of the importance of small seismic events to a monitored CTBT we have begun a survey of globally distributed regional seismic recordings of earthquakes, quarry blasts and explosions with $m_b \sim 2.5$. The first goal of this project is to test the effectiveness of our automated time-frequency discriminant (ATFD) at distinguishing quarry blasts from single explosions and earthquakes using regional array and network recordings. We intend to use these data to develop and test enhancements of the technique and develop complementary discriminants for use when the ATFD proves to be ineffective. As part of this program we intend to determine if a low frequency spectral signature (perhaps caused by source finiteness) might be used for discrimination at far-regional distances. We will analyze these waveforms using the standard multi-taper estimation technique and a new wavelet based technique that will allow us to process 3-component data and analyze the evolution of spectral amplitude and polarization with time and frequency.

The ATFD uses a binary sonogram which is derived from the original, spectral, sonogram by the application of filters which replace local spectral information with a binary code which simply reflects local spectral highs and lows. The ATFD calculates a two-dimensional Fourier transform of the binary sonogram which reveals the dependence of the binary pattern on frequency *and* time. In view of its resemblance to the cepstrum (which identifies periodicities in single spectra), and the fact that it is derived from onset and coda phases we refer to it as the *coda cepstrum*. We are currently working on an adaptive coda cepstrum which iteratively solves for filters that are optimal for extracting any time-independent pattern that exists in the sonogram of an individual event. We are testing this method using recordings of earthquakes and quarry blasts made by the KNET in Kyrgyzstan.

We have conducted a preliminary analysis of network recordings of calibration explosions and quarry blasts made in Kazakhstan by the NRDC network. Using these data we are currently developing a new discriminant that is based on binary sonograms but takes advantage of the independence of ripple-fire waveform spectra from the recording direction. In essence we perform a three-way cross-correlation between binary sonograms derived from the three orthogonal recording channels.

Key Words: coda cepstrum, ripple-fired quarry blast, binary sonogram, wavelets.

1. Objectives

During the term of our existing contract we will expand significantly research we have conducted into the small-event discrimination problem. Our interest has been in using the spectral characteristics of whole regional waveforms to discriminate ripple-fired from non-ripple-fired events (*incl.* earthquakes and single-event explosions). Our objectives are to apply our *automated* whole waveform time-frequency discriminant (ATFD) to large event populations in varied data sets to test transportability and robustness and to enhance the ATFD with more sophisticated processing. In specific we have the following objectives:

1.1 Robustness and transportability

Apply our existing ATFD (*Hedlin et al., 1990*) to a number of dissimilar, well separated, regional data sets with large populations of ripple and non-ripple-fired events to gauge robustness and regional dependence. We propose to apply the technique to vertical component data from several networks and arrays using low (1 to 20 Hz) and broad (1 to 100 Hz) frequency bands. Particular attention will be paid to the cause of outliers. We propose to determine the extent to which array data can suppress noise and increase the range of the ATFD.

1.2 Software development

Enhance the ATFD via (1) wavelet analysis, (2) more advanced spectral analysis techniques [*e.g.* the statistics of Higher Order Crossings (HOC)], (3) advanced processing techniques to permit full use of modern three-component (3C) networks and arrays. 3C data sets examined under objective 1.1 will be re-analyzed to assess improvement.

1.3 Comparisons with other techniques

Analyze the same data sets, discussed under objective 1.1, with a complementary technique (*e.g.* a "regionally trained" spectral ratio method) to assess relative capabilities under different settings. Our intent is to develop a complementary technique that might be merged through evolutionary programming with our own to provide a more comprehensive, multivariate, discriminant. The time-frequency approach, taken alone, will not discriminate between single-event explosions and earthquakes.

1.4 Low-frequency discrimination

Address the question of what low frequency (*e.g.* 1 to 20 Hz) time-independent signature should be produced by mines that use short (*e.g.* 20 ms) delays especially when delay times are irregular. We willto use "ground truth" data to explain any modulations observed at low frequencies and test the theory that they might be due to temporal finiteness of the source (*Hedlin et al., 1990*).

1.5 Contribution of software to database accessing systems

Develop algorithms that are designed to operate on the CSS 3.0 database structure and will be available to all interested parties.

2. Preliminary Research Results

Under previous Air Force contracts (F19628-87-K-0013 and F19628-88-K-0044) we developed a discriminant that seeks long-lived spectral modulations in major phases and the coda. Long lived modulations can be produced by seismic resonance and by ripple firing. *Hedlin et al (1989)* developed a procedure whereby a binary sonogram is derived from the original, spectral, sonogram by the application of filters which replace local spectral information with a binary code which simply reflects local spectral highs and lows. *Hedlin et al. (1990)* produced a procedure to automatically recognize time independent patterns. This Automated Time Frequency Discriminant (now known as the ATFD) calculates a two-dimensional Fourier transform of the binary sonogram which reveals the dependence of the binary pattern on frequency *and* time. In view of its resemblance to the cepstrum (which identifies periodicities in single spectra), and the fact that it is derived from onset and coda phases we refer to it as the *coda cepstrum.* The binary sonogram and the coda cepstrum form the basis for the preliminary research results described below.

In developing this technique *Hedlin et al. (1989)* used a subset of the 1987 NRDC dataset (Figure 1). The NRDC network was deployed in 1987 in central Kazakhstan and made recordings of calibration explosions and quarry blasts at local and regional distances. To further this analysis we have returned to this dataset and are currently analyzing all recorded events. We are also using data recorded by the KNET. The KNET (Figure 1) is a 10 station telemetered 3C broadband network located in Kyrgyzstan. The network has yielded a large number of recordings of earthquakes and quarry blasts at local and regionals distances.

2.1 The NRDC cross correlation analysis. In Figures 2a and 2b we display sonograms calculated from two recordings in the NRDC dataset (originally published in *Hedlin et al., 1989*). As mentioned above the quarry blast (2b) displays a clear time independent modulation superimposed on the larger spectral features (*e.g.* decay with frequency and time). This modulation is almost certainly due to ripple firing at the source. No modulation is present in the sonogram obtained from the recording of the calibration explosion (2a). By converting each spectral estimate to binary form (using boxcar filters spanning 5.0 and 2.5 Hz; the procedure is described in *Hedlin et al., 1989*) we arrive at the binary sonograms displayed in Figure 3. As expected, this conversion has suppressed the large scale features. The binary sonogram calculated using the quarry blast recording contains an obvious time-independent character. As displayed in Figure 4 this character is largely independent of the recording component - unlike the binary sonograms derived from chemical explosions. Taking advantage of this similarity we are developing a discriminant where we cross correlate the 3 pairs of binary sonograms (E-N, N-Z, Z-E) and compute the average cross correlation at zero lag. A preliminary result of this processing is shown in Figure 5. What we see in this figure is that, overall, the borehole cross correlations are lower - particularly at KSU. This is almost certainly due to the effect of near surface seismic resonance. The borehole sensors were located 100 m beneath the free-surface. Considering the borehole recordings we see that event c (#3) does not have the highest three way cross-correlation, it is somewhat above the average of the quarry blasts population. Events 1 and 10 have clearly failed this test - they have less energy in common between the three channels than the calibration explosions. This is clearly not due to an unusually great range from the station (lower figure) but it appears that no spectral modulation (in the band up to 35 Hz) was produced at the source.

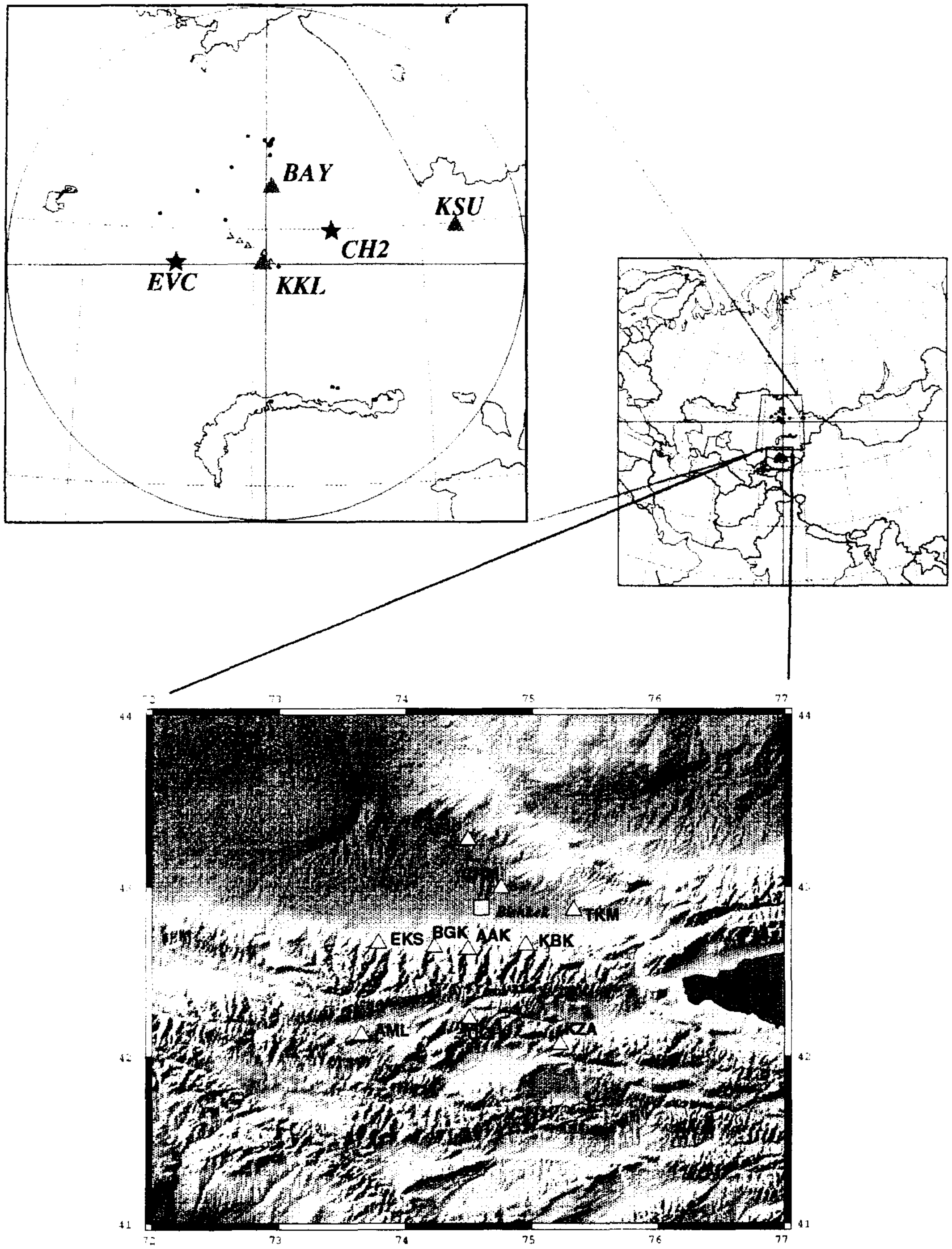

Figure 1. The two datasets considered in this paper come from central Asia. The NRDC dataset (upper left) was collected in 1987. The KNET (lower) is located in Kyrgyzstan on the boundary between the Kazakh platform to the north and the Tien Shan to the sourth.

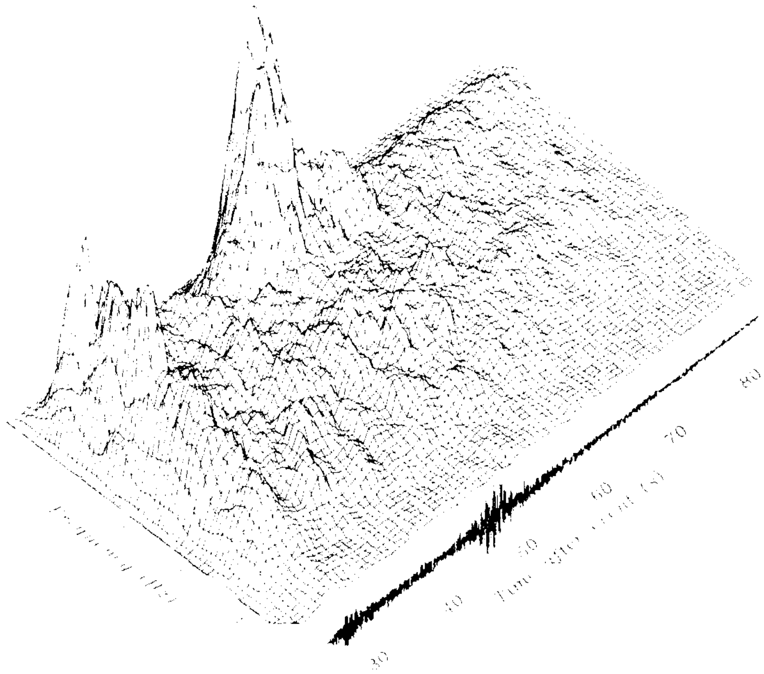

Figure 2a. Seismogram resulting from a single chemical explosion (CH2; Figure 1) detonated in Kazakhstan and corresponding sonogram. The recording was made at a range of 157 km by the vertical component seismometer at Bayanaul.

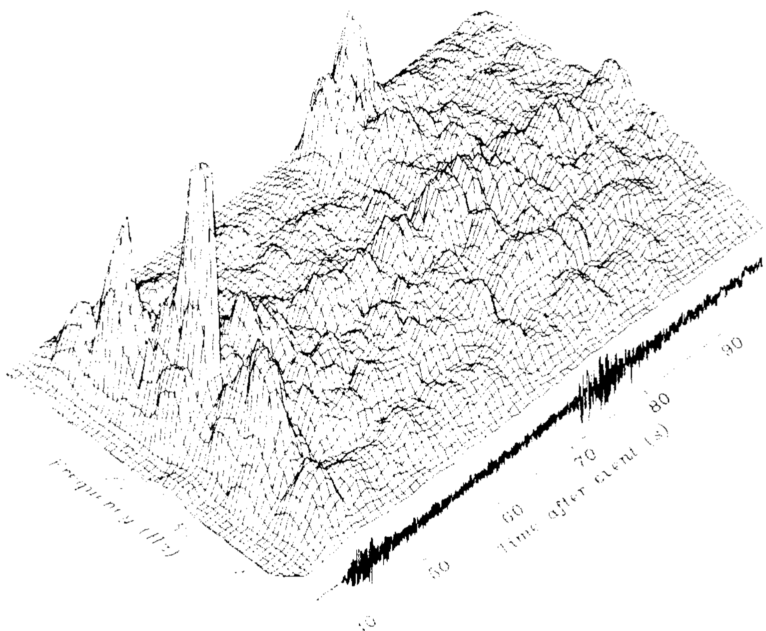

Figure 2b. Seismogram resulting from a ripple-fired quarry blast (EVC; Figure 1) detonated in Kazakhstan and corresponding sonogram. The recording was made at a range of 264 km by the vertical component seismometer at Bayanaul.

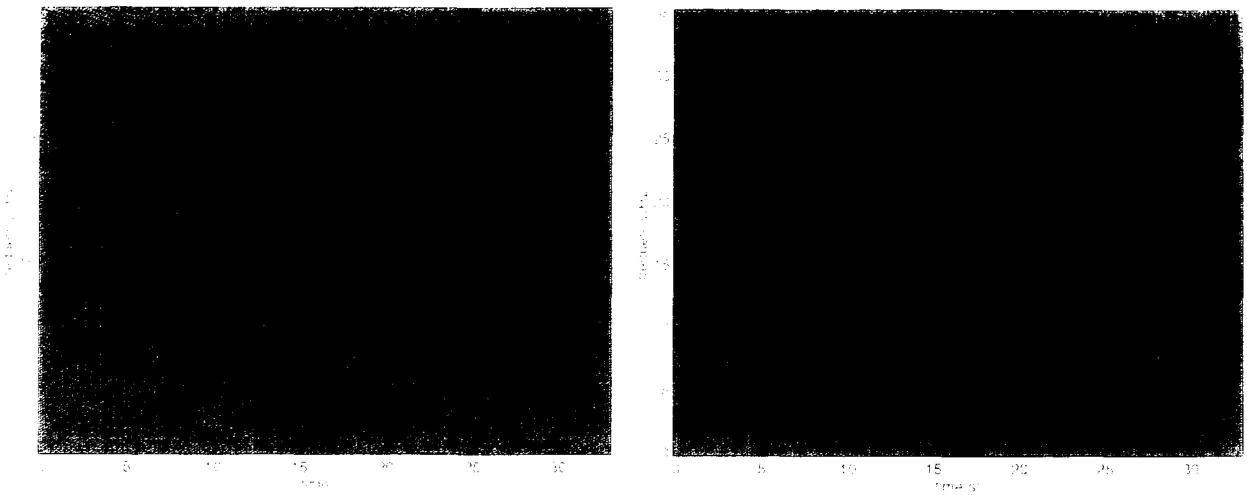

Figure 3. Binary versions of the sonograms presented in Figure 2a (left) and 2b (right).

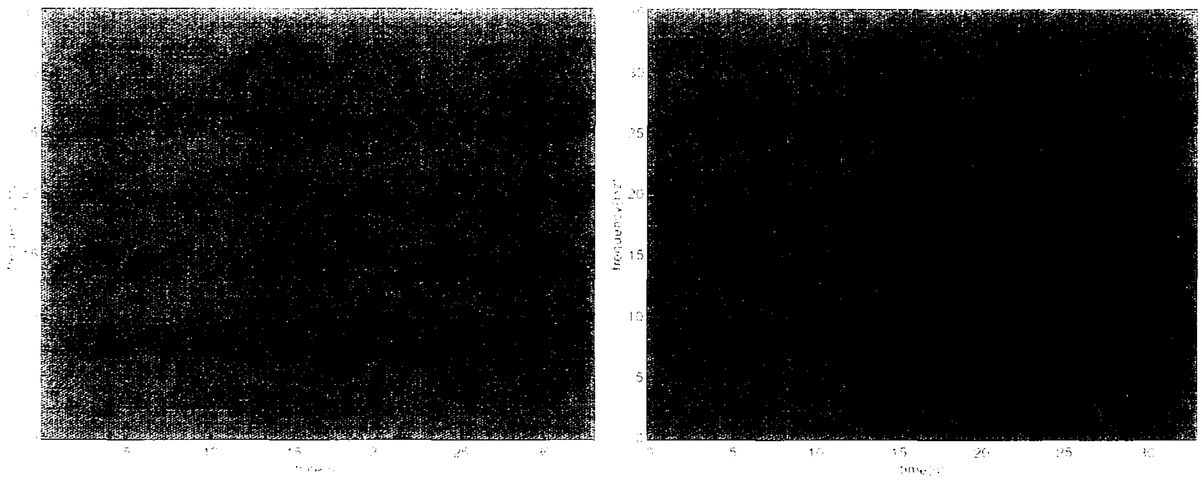

Figure 4. Binary sonograms calculated from the north (left) and east (right) component recordings of event c (Figures 1, 2b and 3).

2.2 An adaptive coda cepstrum calculated using KNET data. One way in which the ATFD might be improved is in the selection of filters used to convert sonograms to binary form. Although quarry blasts come in all sorts of "shapes and sizes" we have, in the past, applied two boxcar filters (via frequency domain convolution) to smooth the spectra and, through differencing, convert them to binary form. The same filters are used for all events. We are currently working on a formalism whereby optimal filters can be obtained for each event. For example, in one approach we make an initial attempt at reducing a sonogram to a binary pattern and, using the information in the resulting coda-cepstrum, iteratively solve for the boxcar filters that will be most effective at extracting the existing time-independent pattern. In Figure 6a we consider a recording of a suspected quarry blast made at 30 km by the KNET station CHM (Figure 1). The sonogram displays significant banding

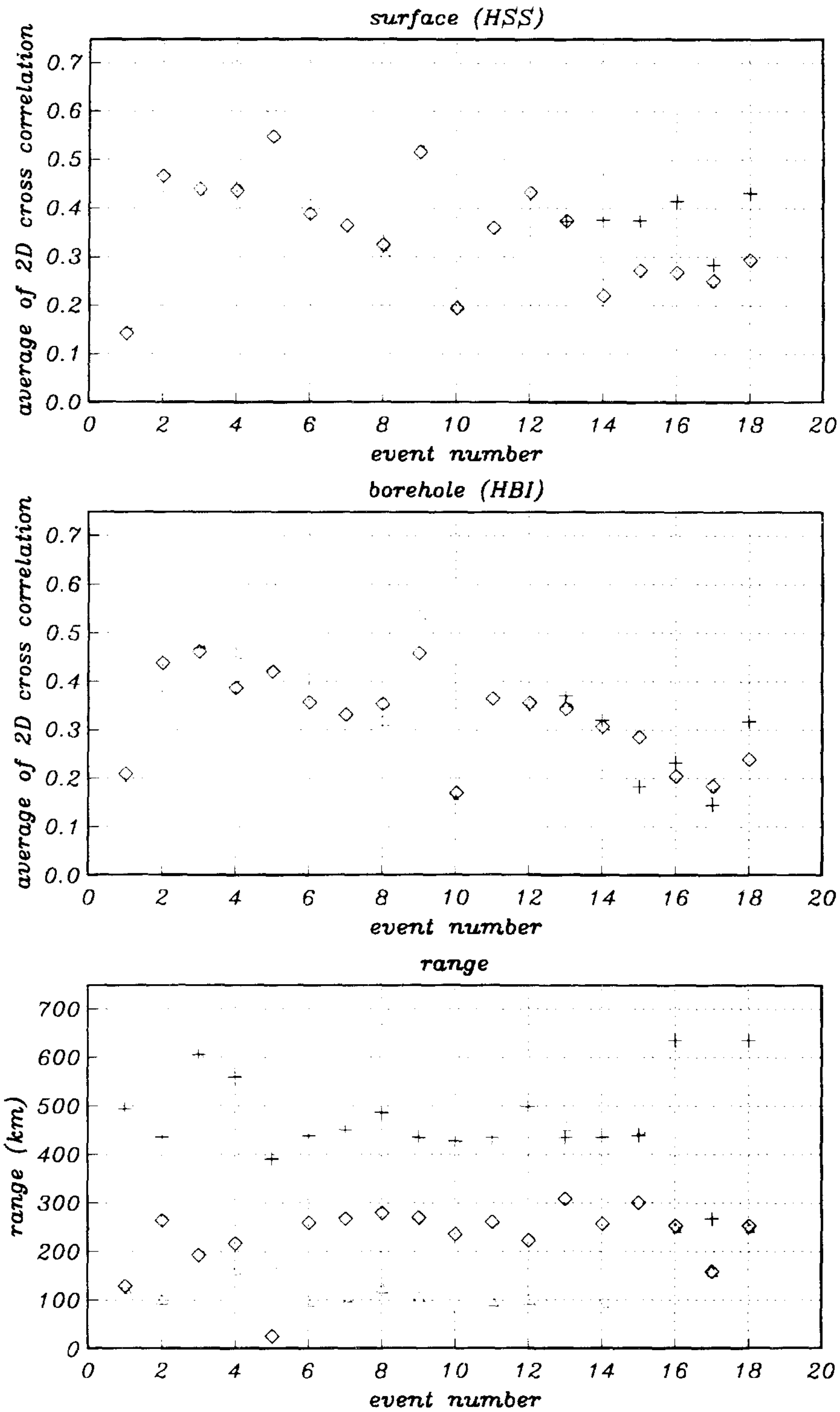

Figure 5. Three way cross correlations from evcnst in the NRDC dataset. Events 1 to 15 are quarry blasts, events 16 to 18 are calibration explosions. The events considered in Figures 2 to 4 are #3 and #17. The triangles, diamonds and crosses represent stations BAY, KKL and KSU. Displayed in the upper and middle figure are results from surface high-gain and borehole high-gain sensors., the lower figure shows source-receiver ranges. A perfect match between all three channels would produce an average cross-correlation of 1.0.

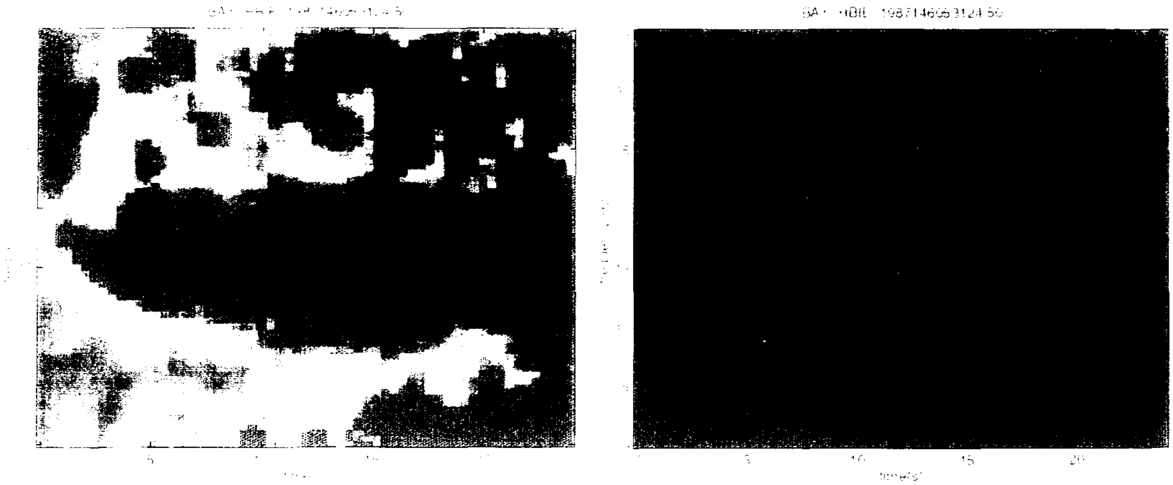

Figure 6a. Sonogram calculated from a CHM recording (east west high-gain channel) of a nearby quarry blast. A binary sonogram displayed on the right was computed using boxcars spanning 5.0 and 2.5 Hz

(independent of time). The binary sonogram (calculated using two boxcars of length 5 and 2.5 Hz) has captured much of this time independent texture. As illustrated in Figure 6b the coda cepstrum has maximum power at a time independent quefrency of .05 s. The coda-cepstral peaks are roughly half the amplitude of peaks that would be obtained from a pattern that is perfectly independent of time. By iteratively varying the boxcar filters to enhance energy at the peak of the coda-cepstrum we arrive at the binary pattern and the coda-cepstrum shown in Figure 6b. The final filters are clearly better suited to this event. Although the improvement is striking it must be noted that the unhindered algorithm will, sometimes, find time independent energy when essentially none is present. We are currently considering ways to control the process to prevent this. This process of tailoring filters to each event can be viewed as an extension of our goal to train the algorithm to different areas.

Recommendations and Future Plans

To a large degree our work in the coming year will be directed toward testing and developing discriminants using globally distributed datasets. We plan to continue our work on the KNET and NRDC data and begin analyses of data recorded by the Pinon Flat Broadband Array and the ANZA network (in southern California), the Geyokcha array in Turkmenistan, the Pinedale research facility in Wyoming and numerous stations in the GSETT-3 network. An important aspect of our work will be in explaining why our discriminants fail (*e.g.* events 1 and 10 in Figure 5). For this purpose datasets with ground truth data will be particularly valuable. One dataset we plan to analyze is the Tyrnyauz Mine data (*Stump et al.*, *1994*). Ultimately we want to determine if a discriminant can be created that is universally applicable, or regionally *trainable* and robust. By analyzing the datasets mentioned above we will be exposing the technique to different mining practice and a different geological setting.

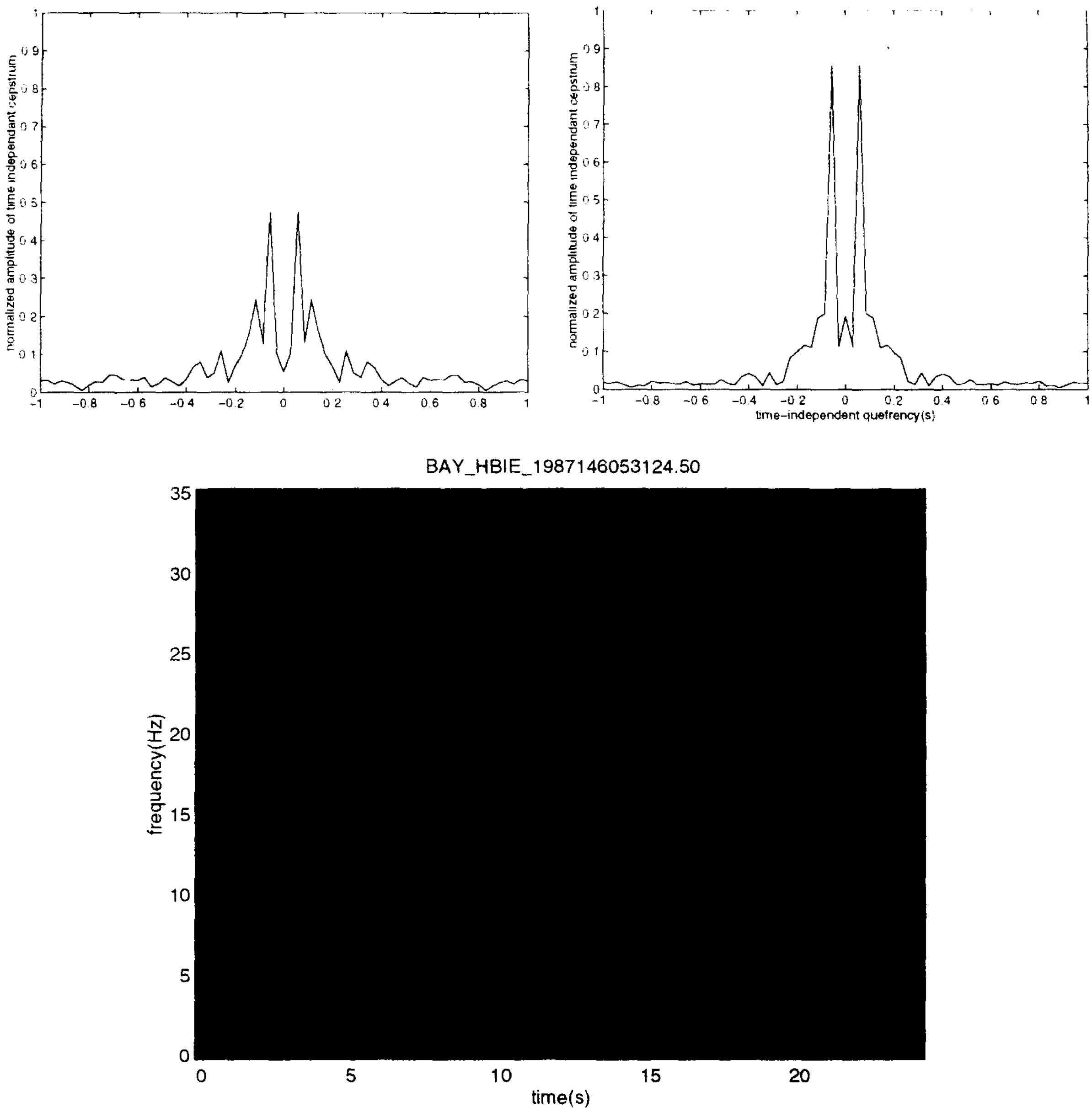

Figure 6b. In the upper left we display the time-independent slice through the coda cepstrum obtained from the binary sonogram displayed in Figure 6a. In the lower part of the figure we display the new binary sonogram obtained using boxcar filters that were chosen after 2 iterations. In the upper right is the final time-independent slice through the coda cepstrum.

In analyzing these data we will, in addition, attempt to answer the following questions:

(1) can earthquakes give rise to time-independent modulations?; (2) under what circumstances will ripple-fired events not yield modulated spectra?; (3) to what extent is success dependent on source-receiver range and azimuth? Using linear superposition theory we will predict the time independent spectral signature that should be present in mine records. Using our ATFD algorithm (*Hedlin*

et al., 1990) we will expand the 3-component recordings into time-frequency displays and investigate the correspondence between the expected and observed time independent signatures. We expect significant discrepancies in some events. The same processing will be applied to any earthquake records. Multiple recordings of the same events, obtained at local to regional distances will allow us to determine the effective range of the discriminant.

(4) are short delay (*e.g.* 20 to 30 ms) ripple-fired events capable of generating robust spectral modulations below 20 Hz? There have been a number of observations of a spectral null at low (< 10 Hz) frequencies (*e.g. Gitterman and Van Eck,1993* observing mines at local ranges in Israel). A null is predicted by linear wavefield superposition and is due to source finiteness. If this is detectable in the events in the aforementioned datasets we will attempt to determine if this spectral quality can be used for discrimination at far-regional distances (O 400 km).

(5) how can the discriminant be improved by using 3C data sets? In the past we have used a multi-taper algorithm to expand time series into time-frequency displays. A short sliding window is used to reveal how the spectral content evolves with time. While taking advantage of the multi-taper's proven ability to yield minimally biased spectral estimates from short time series this approach considers each recorded component separately and thus does not constrain particle motion. Furthermore the resolution is invariant with time and frequency. An alternate means to expand a time series into a time-frequency plane is based on wavelets (*Daubechies*, 1990) which scale with frequency and thus yield increasing temporal resolution with increasing frequency. *Lilly & Park, 1995* have derived multiple, leak resistant, wavelets (similar in concept to the tapers used in multi-taper analysis) to expand 3-component recordings into time and frequency dependent displays of spectral power and polarization. We plan to use the method of Lilly and Park to determine whether these wavelet based amplitude and polarization estimates are useful in identifying ripple-fired events from seismic recordings.

4. References

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